Wavelength Tunability of All-Optical Clock-Recovery Based on Quantum Dash Mode-Locked Laser Diode Under Injection of a 40 Gb/s NRZ Data Stream

Josué Parra-Cetina, Sylwester Latkowski, Ramón Maldonado-Basilio, and Pascal Landais

***Abstract*— Wavelength tunability of an all-optical clock recovery operation based on a quantum dash mode-locked Fabry-Pérot laser diode is experimentally investigated. Synchronization of the device to the injection of 40 Gb/s NRZ incoming data is assessed by analyzing both the carrier-to-noise ratio and the linewidth of the 40 GHz beat-tones measured at the mode-locked laser output. Under optical injection, beat-tone linewidths below 10 Hz are measured. Recovered clock pulses featuring a width of 1.6 ps are obtained irrespective of the wavelength detuning between the laser spectra and the optical carrier of the incoming data stream.**

***Index Terms*—All-optical clock recovery, non-return-to-zero (NRZ), mode-locked laser, quantum dash, Fabry-Pérot laser.**

I. Introduction

All-optical clock recovery (CR) might be an essential technology in future optical networks and optical signal processing as the information is kept in its optical format. Clock recovery operations have been investigated by using mode-locked semiconductor laser diodes (MLLD) [1]-[6]. Such devices have attracted significant attention because of their stable operation, cost effectiveness, low energy consumption and small size, holding possibilities for monolithic integration. Among the different approaches of clock recovery with MLLDs, those based on quantum dot/dash (QDot/QDash) lasers have demonstrated good performance in terms of frequency stability and low timing jitter [5] because of their narrow spectral linewidth and small associated phase noise [5],[7].

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Furthermore, QDash-ML lasers have demonstrated the feasibility to synchronize their free running frequencies with high bit rates at 40 Gb/s and beyond by direct [4],[5] or sub-harmonic frequencies [6], as well as being able to handle both non-return-to-zero (NRZ) and return-to-zero (RZ) modulation formats. Focusing on the assessment of clock-recovery operations based on mode-locked laser diodes, to the best of the authors' knowledge these can be performed either by re-modulating the recovered clock with the original data stream and then implementing bit error rate measurements, or by analyzing the linewidth of the radio frequency (RF) beat-tone signals generated within the MLLD and then retrieving the root-mean-square (rms) timing jitter. In this context, synchronization of a QDash-MLLD subject to the injection of 40 Gb/s NRZ incoming data is investigated in this work. Carrier-to-noise ratio (CNR) and full-width at half maximum (FWHM) of the beat-tones generated by the laser source under study are analyzed. Such an investigation is carried out by setting a detuning between the carrier wavelength of the incoming data and the right-edge wavelength of the QDash laser in the range from 3 to 26 nm. Evaluation of the wavelength detuning in clock recovery based on QDash-ML lasers provides an insight on the optical network management and their potential applications in all-optical regeneration, wavelength conversion and logic gating, for instance. In addition, features of the recovered clock signals in terms of pulse width and timing jitter are analyzed.

II. Passively Mode-locked Quantum Dash laser

The device under investigation is a 1-mm long, DC-biased, multi-mode QDash Fabry-Pérot laser diode [8]. The laser is a single-section device, without phase or saturable absorption sections. Its threshold current is measured at 18 mA and an average power of 1.63 mW is collected by a 0.5 NA lensed fiber when operating at 350 mA and temperature controlled at 25 °C. Within the 3 dB spectral bandwidth, the QDash-MLLD exhibits 40 modes from 1520 to 1532 nm with an inter-modal separation of 0.31 nm, corresponding to a 39.77 GHz free spectral range (FSR). In addition, the linewidth of the longitudinal modes varies from 10 to 45 MHz [9]. Despite being DC-biased, the laser exhibits a passive mode-locking behavior, featuring a periodic variation of its output emission. Mode-locking in this type of laser is attributed to the nonlinearities in the semiconductor active region, mainly sustained by four wave mixing processes [8]-[11]. The frequency of the RF beat-tone is determined by the laser FSR, featuring a FWHM of 25 kHz at free running conditions. In addition, the pulses generated by the QDash-MLLD exhibit a width of 2.2 ps, featuring a time-bandwidth product of around 0.84. Considering a collected power of 1.6 mW and a repetition rate of 40 GHz, pulses exhibit a peak power of 18 mW [9].

III. All-Optical Clock Recovery Results

The experiment investigating the clock-recovery functionality based on a QDash-MLLD operating under injection of an optical data stream is illustrated in Fig. 1(a). A pulse pattern generator (PPG) is utilized for producing a (2^{31}-1)-long pseudo random binary sequence (PRBS) in NRZ format at 40 Gb/s. The PRBS signal is applied onto an optical carrier obtained from a CW laser source through a Mach-Zehnder modulator (MZM) and then amplified with an Erbium-doped fiber amplifier (EDFA-1). An optical band-pass filter (OBPF-1) centered at the data carrier wavelength suppresses part of the amplified spontaneous emission of EDFA-1. Data stream optical power (90 %) is injected into the QDash-MLLD via an optical circulator and a lensed fiber whilst the remaining power is directed to the detection stage. The incoming data signal is preconditioned with a polarization controller (PC-2) and a variable optical attenuator (VOA). Electrical and optical spectra of the data injected to the QDash laser (or equivalently at the output of OBPF-1) are illustrated in Figs. 1(b) and 1(c), respectively. Radio frequency spectrum is obtained after optical to electrical conversion and subtracting the accumulative noise added throughout the detection stage. It features components at 20 and 40 GHz inherent to the operation of the utilized PPG. However, they do not affect the quality of the NRZ wave forms, as illustrated in the optical spectrum depicted in Fig. 1(c). The QDash laser is DC-biased at 102 mA and temperature stabilized at 25 ºC. Signal from the laser output at third port of the circulator is amplified with EDFA-2 and then passed through optical filter OBPF-2. Such a filter has a Gaussian profile and is set to a 1530 nm central wavelength (minimum tunable wavelength achievable in this device) and a 3 dB bandwidth of 2 nm. It is utilized to spectrally isolate the recovered clock at the QDash-MLLD output from the injected data stream, as depicted in Figs. 1(d) and 1(e). The optical clock is then converted to the electrical domain by using a 50 GHz photo-detector (PD) and a 40 GHz RF amplifier (RF-AMP). The electrical clock directed to the detection stage is analyzed with an electrical spectrum analyzer (ESA) and used as a trigger signal for a digital sampling oscilloscope (SCOPE) with 40 GHz precision time base (PTB). An optical spectrum analyzer (OSA) is used to monitor both optical signals, namely the data and the recovered clock.

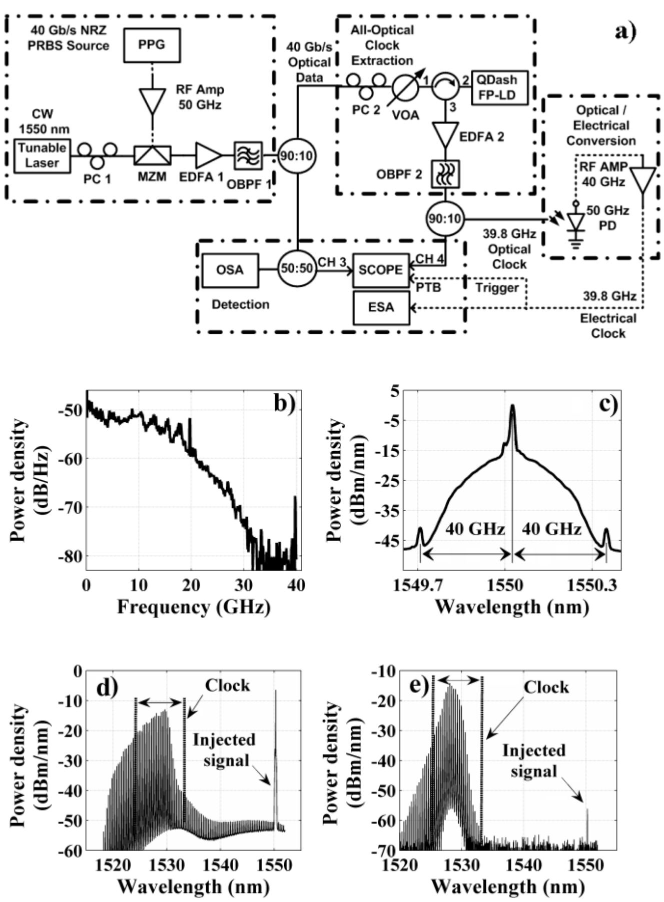

Fig. 1. (a): Experimental setup. Continuous (—) and dashed (---) lines denote optical and electrical links, respectively. (b)-(c): Electrical and optical spectra of the data injected to the QDash-MLLD. (d)-(e): Optical spectra of recovered clock and data signals before and after the OBPF-2, respectively.

The experiment is carried out by injecting a 40 Gb/s NRZ PRBS signal into the QDash-MLLD at various carrier wavelengths whilst maintaining the same average power impinged onto the laser (kept at 12.7 dBm when measured at second port of the circulator). Owing to the coupling efficiency measured as a ratio between the total emitted power and the power collected by the lensed fiber used in the system (for the same bias current and temperature conditions), injection coupling losses of at least 6.44 dB can be assumed. A fine tuning of the state of polarization and average power of the injected data signal, as well as on the DC-bias current supplied to the QDash-MLLD allows for an optimized locking of the laser to the incoming data.

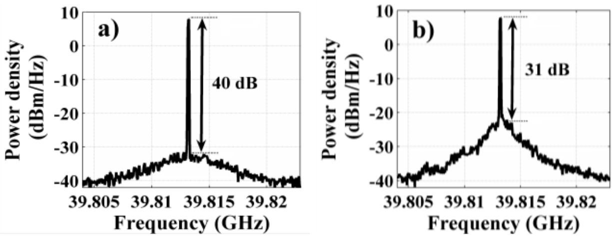

Fig. 2. RF spectra of beat-tones measured at the output of the QDash-MLLD subject to the injection of data signals whose carrier wavelengths are set to 1535 nm (a) and 1550 nm (b).

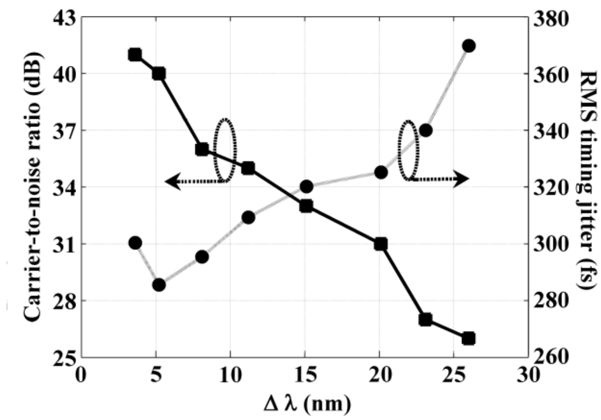

Fig. 3. Carrier-to-noise ratio of the ~40 GHz beat tones and timing jitter of the recovered clock signals in terms of the wavelength detuning between carrier and clock pulses.

As previously stated, the performance of the clock-recovery operation, or in other words the locking of the QDash-MLLD under the injection of a 40 Gb/s NRZ data stream, is assessed by analyzing the radio frequency beat-tone signals obtained at the laser output. The RF spectra of the ~40 GHz beat-tones are depicted in Figs 2(a) and 2(b) for injected data streams whose carrier wavelengths are set at 1535 and 1550 nm, respectively. In these measurements, the ESA is set to a 20 MHz span and 30 kHz resolution bandwidth. As illustrated in Figs. 2(a) and 2(b), the noise contribution on the beat-tone signals changes with the wavelength of the injected data. As a consequence, the carrier-to-noise ratio varies with the carrier wavelength, changing from 40 to 31 dB for carriers at 1535 and 1550 nm, respectively. A complete set of experimental CNR measurements is shown in Fig. 3 for carrier wavelengths ranging from 1533 to 1556 nm. At this point it is important to stress that the synchronization of the QDash-MLLD with NRZ data has been performed in spite of the lack of strong clock tones on the injected signals. Furthermore, a linewidth of ~8 Hz is measured when setting the ESA at a 600 Hz span and 10 Hz resolution bandwidth, regardless of the carrier wavelengths. Such a reduction of the beat-tone linewidth in comparison to that obtained when the QDash-MLLD is operating in passive mode-locking conditions is a signature of the good quality of the external locking process and therefore of the clock-recovery operation [12].

In regards to the characteristics of the recovered clock pulses, on average they feature a temporal width of 1.6 ps and a time-bandwidth product of 0.61, irrespective of the wavelength detuning. Considering a collected power of 1.6 mW and a repetition rate of 40 GHz, the recovered clock pulses exhibit a peak power of 25 mW. In addition, rms timing jitter ranging from 260 to 370 fs is measured with the sampling oscilloscope. As depicted in Fig. 3, an increasing trend in the rms timing jitter is observed with the wavelength detuning resulting from a reduction in the CNR and an increment in the phase noise.

IV. Conclusions

An experimental investigation on the wavelength tunability of a clock-recovery process has been presented. Despite the fact that the injected data signal lacks a strong base-line component at the clock frequency, good performance of the mode-locking process is observed in terms of the CNR and linewidth of the beat-tones at 40 GHz, as well as in the width and rms timing jitter of the recovered clock pulses at the QDash-MLLD output.

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